

# Radio Properties of FIRST Radio Sources at 1 mJy

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## ABSTRACT

This paper presents a detailed analysis of the radio properties for the sample of faint radio sources introduced in Magliocchetti et al. (2000). The sample comprises mainly intrinsically low-power sources whose majority ( $\gtrsim 70$  per cent) is made of FR I radio galaxies. These objects show some degree (at  $1\sigma$  confidence level) of luminosity evolution, which is also needed to correctly reproduce the total number and shape of the counts distribution at 1.4 GHz. Analysis of the de-evolved local radio luminosity function shows a good agreement between data and model predictions for this class of sources. Particular care has been devoted to the issue of ‘lined’ galaxies (i.e. objects presenting in their spectra a continuum typical of early-type galaxies plus emission lines of different nature), which appear as an intermediate class of sources between AGN-dominated and starburst galaxies. Different evolutionary behaviours are seen between the two sub-populations of lined and non-lined low-power radio galaxies, the first class indicating a tendency for the radio luminosity to decrease with look-back time, the second one showing positive evolution. We note that different evolutionary properties also seem to characterize BL Lacs selected in different bands, so that one might envisage an association between lined FR I and the sub-class of BL Lacs selected in the X-ray band. Lastly, we find evidence for a negligible contribution of starburst galaxies at these low flux levels.

**Key words:** galaxies: active - galaxies: starburst - Cosmology: observations -radio continuum galaxies

## 1 INTRODUCTION

During the last twenty years, attempts to derive models for the description of the space density and evolution of radio sources have mainly taken two tacks: the first approach bases its predictions on the unification paradigm (see e.g. Urry & Padovani 1995), while the second one relies on the evolutionary behaviour of the galaxy hosting the radio source.

Models based on the unification paradigm (Orr & Brown 1982; Padovani & Urry 1992; Maraschi & Rovetti 1994; Wall & Jackson 1997 just to mention a few) stem from the “relativistic jet” model by Blandford & Rees (1978), where non-thermal continuum radiation is emitted by plasma relativistically moving along the jet axis. As a necessary consequence one has that, as the radio axis gets aligned with the line of sight, the radio source appears as *core-dominated*, i.e. flat-spectrum beamed radiation dominates the radio emission. In the opposite case of misaligned jet axes, the observed flux mainly comes from the extended isotropically radiating structures (lobes) of the source, giving rise to steep-spectrum radio emission. It follows that the latter objects can be considered as the “parents” of flat-spectrum sources, their different appearance only depending on the angle between the beaming axis and line of

sight. A further division can then be made according to the morphology and/or intrinsic power of the sources: at low radio powers FR I galaxies (Fanaroff & Riley 1974) are assumed to be the parent population of BL Lac objects, while at higher powers Flat and Steep Spectrum Radio Quasars (FSRQ/SSRQ) are supposed to be the beamed version of FR II galaxies. Note however that this division is somehow fuzzier (e.g. Antonucci 1993; Owen & Ledlow 1994). According to unification-paradigm based models, one therefore has that sources belonging to the same intrinsic population (e.g. FR I and BL Lacs) must display the same evolutionary properties.

A different approach used by a number of authors (Wall, Pearson & Longair 1980; Danese et al. 1987; Dunlop & Peacock 1990; Condon 1984; Rowan-Robinson et al. 1993) - though still dividing radio sources in steep and flat spectrum populations - models their evolution and space density by using descriptions of the epoch-dependent luminosity function. At variance with the previous case, these models do not explicitly assume any physical process for the radio-emission and only focus on the behaviour of the host galaxies.

One of the main limitations affecting these two classes of models (but especially those deriving from the unification

paradigm) is due to the fact that they were mainly based on datasets including very powerful sources ( $S_{1.4\text{GHz}} \simeq 1 \text{ Jy}$ ), and their predictions at faint flux densities greatly diverge because of an inadequate definition of the low-power tail of the AGN radio luminosity function. Models belonging to the second class (Danese et al. 1987; Condon 1984; Rowan-Robinson et al. 1993) push their analysis down to much lower flux densities ( $S \sim 0.1 \text{ mJy}$ ), and assume the contribution to the radio population at  $S \lesssim 10 \text{ mJy}$  to be mainly given by a new class of objects which greatly differ from the radio AGN dominating at higher fluxes. The nature and level of contribution to the total mJy counts of this population is still under debate. For instance Condon (1984) suggests a population of strongly-evolving normal spiral galaxies, while others (Windhorst et al. 1985; Danese et al. 1987) claim the presence of an actively star-forming galaxy population.

This paper presents an analysis of the radio properties for the sample of sources introduced in Magliocchetti et al. (2000, hereafter MA2000). As it will be discussed later on, despite its relative smallness, this sample represents the first attempt to derive spectroscopy directly from objects uniquely identified as radio-emitting sources (i.e. without prior optical identifications). Luminosity functions and luminosity distributions will be derived down to radio-powers  $P_{1.4\text{GHz}} \sim 10^{20} [\text{W Hz}^{-1}\text{sr}^{-1}]$ , therefore allowing a direct comparison with the models introduced earlier on at such low powers. We will also analyze the space density for the different classes of radio-sources and their relative contribution to the total number counts at flux densities  $1 \text{ mJy} \lesssim S_{1.4\text{GHz}} \lesssim 10 \text{ mJy}$ .

The layout of this paper is as follows: Section 2 describes the radio, photometric and spectroscopic properties of the dataset used in our analysis, while Section 3 deals with the luminosity evolution of radio sources and presents the results for the luminosity function. Section 4 discusses these findings within the framework of number counts by comparing observations with model predictions. Section 5 summarizes our conclusions. Throughout this work we will assume  $H_0 = h_0 \cdot 100 \text{ km s}^{-1}$ , with  $h_0 = 0.5$  and  $\Omega_0 = 1$  ( $q_0 = 0.5$ ).

## 2 THE RADIO SAMPLE

The sample used for the following analysis has been derived from the FIRST (Faint Images of the Radio Sky at Twenty centimeters) Survey (Becker, White & Helfand 1995) which includes sources down to  $\sim 0.8 \text{ mJy}$ . The surface density of objects in the catalogue is  $\sim 90$  per square degree, though this is reduced to  $\sim 80$  per square degree if we combine multi-component sources (e.g. sources presenting lobes and hot-spots; Magliocchetti et al. 1998). The catalogue has been estimated to be 95 per cent complete at  $2 \text{ mJy}$  and 80 per cent complete at  $1 \text{ mJy}$  (Becker, White & Helfand 1995).

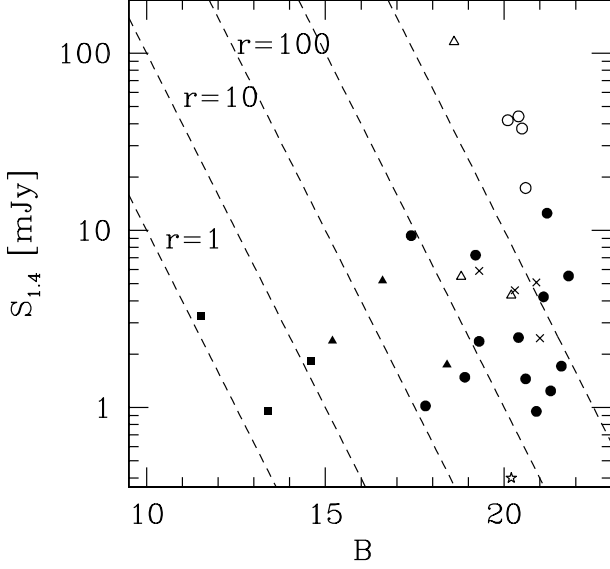
From this catalogue MA2000 considered 8 regions of approximately  $1 \text{ deg}$  each in diameter and performed “blind” (i.e. without prior optical identification of the objects) multi-object spectroscopy by placing fibers at the positions of 365 radio sources ( $\sim 69$  per cent of the radio sample; this percentage was mainly due to the geometry of the spectrograph). From these spectra it was possible to measure 46 redshifts,  $\sim 13$  per cent of the targeted objects. APM data

have then provided photometric information for most of the sources with measured redshifts. Photometry shows that redshift measurements were obtained for objects brighter than an apparent magnitude of  $R \simeq 20.5 \text{ mag}$ , and the sample was estimated to be  $\sim 100$  per cent complete to  $R=18.6 \text{ mag}$ . This value was derived by considering the sources which had photometric measurements but lacked of spectroscopic ones as a function of their radio fluxes. It turned out that all the objects with  $R \leq 18.6$  were endowed with a redshift estimate, independent of the radio flux (Figure 6 in MA2000). The above result implies no radio-bias in the acquisition of the spectra, the only remaining bias being related to the optical properties of the sources.

The objects found with  $R \lesssim 20.5$  were a mixture of early-type galaxies (i.e. absorption systems presenting at most a weak OII emission line which we will hereafter denote as Early) at relatively high redshifts,  $z \gtrsim 0.2$  (24,  $\sim 52$  per cent of the sample), ‘lined’ galaxies (absorption systems presenting strong OII, OIII,  $H\alpha$ ,  $H\beta$  emission lines denoting either ongoing star-formation activity or the presence of an AGN or eventually superposition of both these effects) at intermediate redshifts,  $0.02 \lesssim z \lesssim 0.2$  (8,  $\sim 17$  per cent), and very local starburst (SB) galaxies with  $z \lesssim 0.05$  (3,  $\sim 6$  per cent). By using the diagnostic emission line ratios of Rola, Terlevich & Terlevich (1997), we find four of the lined galaxies to show features principally due to star-formation (E+SF), while the remaining four to be mainly dominated by AGN activity (E+AGN). Note that our findings are consistent with the existence of a significant fraction ( $\sim 10$  per cent) of lined objects amongst low power radio galaxies (Hine & Longair 1979). MA2000 also found a number of broad-lined AGN (type I RL), all at  $z \gtrsim 0.8$  (5,  $\sim 11$  per cent of the sample), two narrow-lined AGN (type II RL) (4 per cent), and 4 stars<sup>\*</sup>. Three objects (respectively one type II RL, one early-type galaxy and one starburst galaxy) were subsequently removed from the original sample by requiring  $S_{1.4\text{GHz}} \geq 1 \text{ mJy}$ . Other seven sources exhibit featureless spectra, showing a continuum emission without the presence of either emission or absorption lines. These unclassified objects, endowed with faint ( $R \gtrsim 18.6$ ) optical magnitudes, could be either associated to low-signal-to-noise-spectra early-type galaxies or to low-power BL Lacs. As they do not have redshift determinations, they will only be considered in the last Section when dealing with the number counts. Their effects on the statistical significance of the sample under consideration will instead be discussed in the Conclusions.

All the early-type and lined galaxies present absolute magnitudes distributed about the mean value  $M_R = -23.1$  with very little scatter ( $\sim 0.5$  at the  $2\sigma$  level) independent of redshift, implying that passive radio galaxies are reliable standard candles, as already discussed by e.g. Hine & Longair (1979). The small spread in magnitude allows us to determine a very tight  $R$ - $z$  relationship for the objects under exam. From this relation MA2000 estimate  $\sim 100$  per cent completeness for the spectroscopic sample with radio fluxes

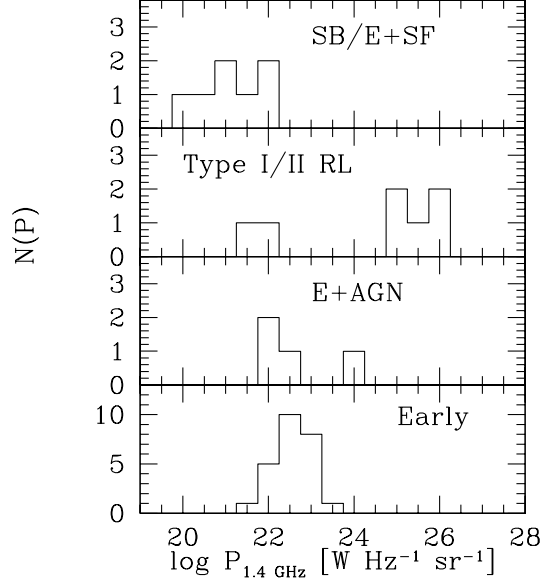
<sup>\*</sup> As the objects cannot be classified as flat/steep radio sources, in the following we name as type I/II Radio Loud (RL) those objects which are radio-loud ( $r > 10$ , see below) with broad/narrow emission lines in the optical spectrum.



**Figure 1.** Radio flux at 1.4 GHz as a function of B magnitude. Filled dots identify early-type galaxies, triangles 'lined' galaxies (filled for E+SF sources, empty for E+AGN objects), filled squares are for starbursting galaxies, empty circles for type I RL, while stars are for type II RL and crosses for unclassified objects (possibly identified as BL Lacs). The dashed lines correspond to constant values of the radio-to-optical ratio  $r = 1, 10, 100, 1000, 10^4$  (see text for details).

$S_{1.4\text{GHz}} \geq 1$  mJy up to  $z = 0.3 \pm 0.1$ . Throughout the paper we will therefore adopt  $z = 0.3$  as the maximum redshift for completeness of the sample. This assumption implies that all the early-type and lined galaxies with redshifts within  $z_{\text{lim}} = 0.3$  will be considered in the subsequent analyses, regardless of their optical magnitude. Note that this limit, given the spread in the R-z relationship, does not exactly correspond to a magnitude cut at  $R=18.6$ . In fact, we find two sources in the sample (both early-type galaxies) which present  $z < 0.3$  and  $R > 18.6$ , even though no objects are detected with  $R \leq 18.6$  and  $z > 0.3$ . This spread might then suggest the existence of  $z \leq 0.3$  and  $R \geq 18.6$  sources, possibly corresponding to the unclassified sources we previously referred to, which were not spectroscopically identified in the MA2000 sample. Since the majority of these objects is expected to present redshifts  $\gtrsim 0.2$  (sources with  $R > 18.6$  and  $z \simeq 0.1$  would correspond to a  $\sim 8\sigma$  event with respect to the R-z relationship and should consequently be extremely rare), in order to assess the importance of this possible cause of incompleteness, the analysis performed in Section 3 will also consider two different samples, derived from the original one by respectively considering cuts at  $z = 0.2$  and  $z = 0.25$ . Results obtained in this way will be then compared with those derived for  $z \leq 0.3$  sources.

Figure 1 shows the distribution of radio fluxes for all the objects in the sample with measured B magnitudes as a function of this latter quantity. The dashed lines indicate different values of the radio-to-optical ratio  $r$ , defined as  $r = S_{1.4\text{GHz}} \times 10^{\frac{(B-12.5)}{2.5}}$ , where S is the radio flux (in mJy) and B is the apparent magnitude in the blue band. Note that, according to the definition of radio-loudness (see e.g. Urry & Padovani 1995), the three starburst galaxies



**Figure 2.** Distribution of monochromatic radio power at 1.4 GHz for the 6 classes of sources discussed in the paper.

with  $r \lesssim 10$  cannot in principle be considered as radio-loud. Also note that, amongst lined galaxies, sources with spectra principally showing signatures due to star formation (represented by filled triangles in Figure 1) and sources where emission lines mainly originate from AGN activity (empty triangles in Figure 1) occupy different regions in the B-S plane, the former objects presenting radio-to-optical ratios closer to those obtained in the case of starburst galaxies. With some confidence we can then conclude that the radio signal emitted by this first group of sources mainly stems from intense star-formation activity, in close resemblance with the case for starburst galaxies.

Figure 2 shows the distribution of monochromatic radio-power  $P_{1.4\text{GHz}} = S_{1.4\text{GHz}} D^2 (1+z)^{3+\alpha}$  (in units  $\text{W Hz}^{-1} \text{sr}^{-1}$ ) for the different classes of objects introduced earlier on. In the above formula  $D$  is the angular diameter distance and  $\alpha$  is the spectral index of the radio emission ( $S(\nu) \propto \nu^{-\alpha}$ ). As we did not have measured values for this latter quantity, we assumed  $\alpha = 0.5$  for type I RL,  $\alpha = 0.75$  for early-type galaxies (with or without emission lines due to AGN activity),  $\alpha = 0.7$  for type II RL and  $\alpha = 0.35$  both for starbursts and E+SF (see e.g. Oort et al. 1987). In the central panel of Figure 2 we grouped together type I and II RL, type I showing higher radio-power; starbursts and E+SF galaxies are also grouped together in the top panel of Figure 2, E+SF sources all appearing for  $P_{1.4\text{GHz}} \gtrsim 10^{21} [\text{W Hz}^{-1} \text{sr}^{-1}]$ . As one can see from the Figure, early-type galaxies with no emission lines follow with good approximation the same distribution in power as those presenting in their spectra emission lines due to AGN activity. Given that their radio-powers are always (apart from one case)  $P_{1.4\text{GHz}} \lesssim 10^{23.5} [\text{W Hz}^{-1} \text{sr}^{-1}]$ , we classify these two subpopulations as FR I galaxies, with the possible exception of the source with  $P_{1.4\text{GHz}} \simeq 10^{24} [\text{W Hz}^{-1} \text{sr}^{-1}]$ . Note that, as already briefly discussed in the Introduction, the distinction between FR I and FR II galaxies seems to be more complicated and not just determined by the values of their

radio power. As Ledlow & Owen (1996) have shown, the FR I/FR II division is also a strong function of the optical luminosity of the host galaxy, optically brighter FR I sources appearing for higher radio powers. Our conclusions for these galaxies to all belong to the same class of FR I is however not affected by the previous statement, as the objects in our sample present  $P < 10^{24} [\text{W Hz}^{-1}\text{sr}^{-1}]$ , threshold below which only members of the FR I population are found, independent of their magnitude. From a morphological point of view we find that all the radio images for these objects show point-like structures. Since the angular resolution of the FIRST survey is  $\sim 5$  arcsec, corresponding to a physical scale of  $\sim 7$  kpc at  $z = 0.05$  and  $\sim 35$  kpc at  $z = 0.3$  for the cosmology adopted in the Paper, one can exclude the presence of very extended structures such as those typical of FR II sources. This further supports our conclusion for these objects to belong to the class of FR I galaxies.

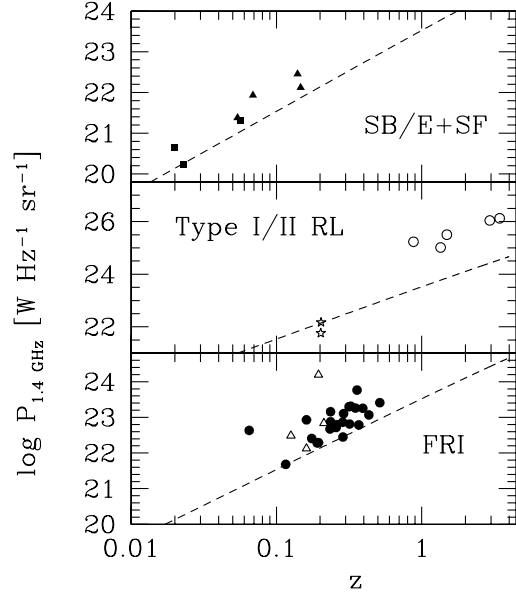
As expected, the three starburst galaxies show low radio-powers ( $P_{1.4\text{GHz}} \lesssim 10^{21} [\text{W Hz}^{-1}\text{sr}^{-1}]$ ), while type I RL all appear for  $P_{1.4\text{GHz}} \gtrsim 10^{25} [\text{W Hz}^{-1}\text{sr}^{-1}]$ .

### 3 STATISTICAL AND EVOLUTIONARY PROPERTIES OF THE POPULATIONS

In principle, in order to directly estimate the evolution of the different radio populations with time, one has to calculate their luminosity functions (LF) in different redshift intervals. Unfortunately though, the sample under consideration does not include enough sources, and therefore we have to apply the Schmidt's  $V/V_{\text{max}}$  test, where  $V$  is the comoving volume ‘enclosed’ by an object and  $V_{\text{max}}$  is the maximum volume within which such an object could have been detected above the radio flux and magnitude limit of the survey. In absence of evolution one has that the quantity  $V/V_{\text{max}}$  is uniformly distributed between 0 and 1, with 0.5 as mean value (Schmidt 1968).

As already stated in Section 2, for the estimate of the quantity  $\langle V/V_{\text{max}} \rangle$  we assumed a completeness limit of  $z_{\text{lim}} = 0.3$  in the case of FR I galaxies (i.e. Early and E+AGN sources) with  $S \geq 1$  mJy. Errors for  $\langle V/V_{\text{max}} \rangle$  are then calculated as  $\Delta(\langle V/V_{\text{max}} \rangle) = (12N)^{-1/2}$  (Schmidt 1968), where  $N$  is the number of objects belonging to this class. Note that we will not include in our analysis either type I/II RL or starburst galaxies (even though we show their evolutionary trends in Figure 3 which illustrates the monochromatic power at 1.4 GHz as a function of redshift), as their small numbers do not allow any meaningful statistics; furthermore, starburst galaxies do not in principle belong to the population of radio-loud sources (see Section 2).

For the population of FR I galaxies (18 sources with  $z \leq 0.3$ ) one gets  $\langle V/V_{\text{max}} \rangle = 0.57 \pm 0.06$ . Note that this result - even though compatible with the hypothesis of no evolution just above the  $1\sigma$  level - seems to disagree with previous findings (see e.g. Urry, Padovani & Stickel, 1991; Padovani & Urry, 1992; Maraschi & Rovetti, 1994; - where the samples were extracted from surveys with much higher flux limits, e.g. the 2 Jy sample (Wall & Peacock 1985) or the 3CR sample (Laing et al. 1984) - and Rowan-Robinson et al., 1993; - where the sample included objects down to  $S_{1.4\text{GHz}} \simeq 0.1$  mJy (Benn et al. 1993)) for the class of FR I not to evolve with look-back time.



**Figure 3.** Monochromatic power at 1.4 GHz as a function of redshift for the classes of objects discussed in the paper. In the lower panel, filled dots are for early-type galaxies, while empty triangles indicate lined galaxies of AGN origin (E+AGN). In the upper panel, squares are for starbursts and triangles for lined galaxies of star-forming origin (e.g. E+SF, see text for details). In the middle panel, open circles are for type I RL and stars for type II RL. The dashed lines show the 1 mJy limit of our sample.

As already anticipated in Section 2, in order to investigate the stability of our results on FR I galaxies with respect to the eventual presence of incompleteness effects in the  $z \leq 0.3$  sample, we repeated the  $V/V_{\text{max}}$  analysis for different redshift cuts. Even though going to lower redshifts automatically reduces the number of sources within the sample and the statistical significance of the measurements, we nevertheless find  $\langle V/V_{\text{max}} \rangle = 0.62 \pm 0.07$  and  $\langle V/V_{\text{max}} \rangle = 0.67 \pm 0.10$  for objects respectively within  $z = 0.25$  and  $z = 0.2$ , in good agreement with our previous findings, showing that incompleteness is not a problem in this case. We can therefore confidently conclude that the sample under exam is well suited to examine the evolutionary properties of FR I galaxies. It is also interesting to note that the above numbers seem to further strengthen the results for positive luminosity evolution of the FR I population.

At this point it is worth spending a few lines on the effects of the class of lined galaxies on the analysis performed so far. The choice of making a distinction between galaxies which presented in their spectra lines of mainly stellar origin (E+SF) and those which indicated the presence of an AGN in their core (E+AGN) has been based on the relative strength of emission line ratios (see Section 2). However, it is possible to note that there is indeed a smooth transition between these two classes of objects, not only in the relative strength of the different emission lines, i.e. whether more due to star formation rather than AGN activity, but also in the radio-power, radio-to-optical ratio and redshift distribution (see Figures 1,2,3 and Table 1) of these sources. Also, if one confines the analysis to radio-power and radio-morphology

**Table 1.** Redshift, radio-to-optical ratio and radio power for the lined sources described in the text, ordered for increasing power. The Table also divides sources into two sub-classes according to their spectral features (i.e. whether mainly indicating signatures of star-formation activity (E+SF) or the presence of an AGN (E+AGN)).

Object	Type	Redshift	$r$	$P_{1.4\text{GHz}} [\text{W Hz}^{-1} \text{ sr}^{-1}]$
2244_086	E+SF	0.054	28.61	$2.4 \cdot 10^{21}$
2244_006	E+SF	0.069	226.6	$8.58 \cdot 10^{21}$
2244_044	E+SF	0.147	398.6	$1.32 \cdot 10^{22}$
2236_012	E+AGN	0.161	?	$1.33 \cdot 10^{22}$
ELAIS2_017	E+SF	0.14	?	$2.82 \cdot 10^{22}$
2244_029	E+AGN	0.126	1815	$3.55 \cdot 10^{22}$
2236_023	E+AGN	0.212	5158	$6.85 \cdot 10^{22}$
2236_013	E+AGN	0.195	3.195e+04	$1.56 \cdot 10^{24}$

only, all these objects would be identified as FR I galaxies. In principle one cannot therefore exclude all the lined galaxies to be indeed members of the FR I population, relative emission line strengths simply reflecting a passage between more AGN dominated to more star-formation dominated sources within the class of FR I. Note that, in general, it is quite common to find “composite” galaxies containing both a starburst and an AGN (see e.g. Hill et al., 2001). In this case, lined FR I galaxies as a whole would be seen as a “bridge” (also meant in the sense of decreasing look-back times) between AGN-fuelled objects (i.e. those presenting spectra typical of early-type galaxies) and sources where the radio signal is dominated by processes connected with the intense star-formation activity (starbursts).

The issue connected with these “transition” objects is quite delicate as their eventual presence or absence within the class of FR I galaxies can modify the apparent evolutionary properties of this population. In fact, if we consider as FR I all the lined galaxies (i.e. E+AGN and E+SF) and not only those where emission lines seem to mainly stem from AGN activity, the value for  $\langle V/V_{\text{max}} \rangle$  decreases to  $0.52 \pm 0.06$ , in this case perfectly compatible with no evolution. It follows that one has to devote particular care in treating these sources as they might influence eventual conclusions. We stress that this effect should not depend on the statistical significance of the sample, since lined galaxies are in general expected to make up for  $\sim 20$  per cent of low-to-intermediate redshift radio samples (see e.g. Sadler et al., 1999).

More stable results are instead those separately related to the two sub-populations of Early and E+AGN. For the first class of objects in fact we find  $\langle V/V_{\text{max}} \rangle = 0.60 \pm 0.07$  - compatible with *positive* evolution at the  $2\sigma$  level -, while  $\langle V/V_{\text{max}} \rangle = 0.35 \pm 0.14$  - suggesting *negative* evolution - in the case of E+AGN FR I. Even though the paucity of sources here does not allow any strong statement, it is nevertheless worth noticing that this negative trend also seems to hold if one considers all the lined galaxies together, whatever the origin of the lines is, for which  $\langle V/V_{\text{max}} \rangle = 0.33 \pm 0.10$ . In general we find early-type galaxies to show positive luminosity evolution, while lined galaxies tend to evolve in a negative way. The bottom line in this case seems to be that, even though belonging to the same population of FR I, these two classes of E and E+AGN sources show quite different evolutionary behaviours; their combination gives rise to a mildly evolving trend for FR I galaxies as a whole, but this

result might hide an internal dichotomy and requires further investigation.

Note that these different (and opposite) evolutionary trends could mirror the behaviours established for the beamed population of BL Lac objects, respectively as lower power ‘X-ray selected’ type and higher power ‘radio selected’ sources. In this respect, models which postulate the evolutionary connection between positively evolving radio-loud quasars into negatively evolving BL Lacs (Cavaliere & Malquori 1999) should refer to the sub-population associated with E+AGN galaxies only.

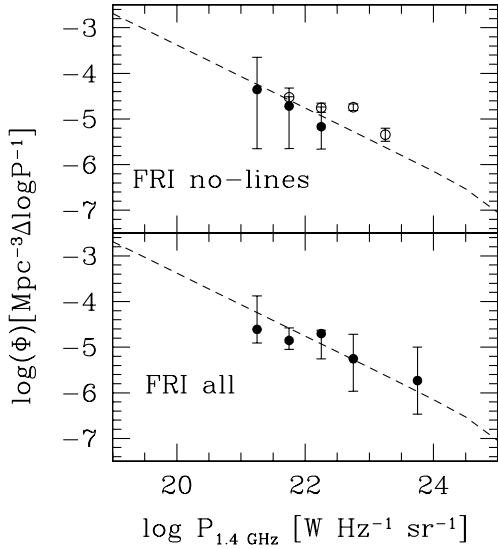
While keeping the above warnings in mind, in the following analysis we will rely on the division made amongst lined galaxies introduced in Section 2 when describing the spectroscopic sample. We will then consider as belonging to the FR I population only early-type galaxies plus those lined galaxies where emission lines were mainly of AGN origin (E+AGN). For this sample we have then estimated the degree of evolution and obtained the local radio luminosity function (LF) to be compared with model predictions. We parameterize the evolution as  $P(z) = P(0) \exp^{t(z)/\tau}$  (pure luminosity evolution PLE), where  $t(z)$  is the look-back time in units of the Hubble time (defined as  $t(z) = \int_0^z 1/[(1+z')^2(1+\Omega_0 z')]^{1/2}]$ ) and  $\tau$  is the time-scale of the evolution in the same units; the best values for  $\tau$  are found by requiring  $\langle V/V_{\text{max}} \rangle = 0.5 \pm (\frac{1}{12N})^{1/2}$ , while the local power  $P_{1.4\text{GHz}}(0)$  can be obtained by inverting the expression for luminosity evolution.

According to this approach, one then finds  $\tau = 0.17^{+0.50}_{-0.10}$  for FR I galaxies, compatible with positive evolution at the  $1\sigma$  level. Note that, by restricting this analysis to the sub-classes of early-type and E+AGN galaxies separately, one would get  $\tau \sim 0.06$  for the first case and  $\tau \sim -0.05$  in the second one. The statistical significance of these results is however limited by the small dimensions of both samples together with the limited redshift range ( $0 \leq z \leq 0.3$ ) allowed to consider the effects of any eventual evolution.

The above values for the evolution parameter  $\tau$  have then been used to derive the local LF by de-evolving at  $z=0$  the luminosity of each source and by subsequently grouping the sources in bins of  $\Delta \log P = 0.5$ . The LF has been obtained according to the expression

$$\Phi(P) = \sum_i N_i(P, P + \Delta P) / V_{\text{max}}^i(P), \quad (1)$$

where  $N_i$  is the number of objects with luminosities between



**Figure 4.** Local radio luminosity function at 1.4 GHz for the whole sample of FR I galaxies (lower panel) and the sub-class of FR I with no emission lines in their spectra (Early - upper panel). Error-bars are given by the sum in quadrature of the Poisson errors and the variations of the number density associated to a  $1\sigma$  change of the evolution parameter  $\tau$ . Note that we only include objects with  $z \leq 0.3$ , our completeness limit, and  $S \geq 1$  mJy. Dashed lines indicate the Dunlop & Peacock (1990) model for pure luminosity evolution (see text for details). Filled circles in the upper panel correspond to the local LF under the hypothesis of luminosity evolution with  $\tau = 0.06$ , while open circles are obtained in the case of no evolution (see text for details).

$P$  and  $P + \Delta P$ , and  $V_{\max}^i(P)$  is their maximum volume, calculated as in Section 3. The values for the LF have then been corrected by means of the factor  $0.8 \times 0.66$  to take into account the 80 per cent completeness of the FIRST survey at 1 mJy (see Becker et al., 1995) and the percentage of sources with fibres placed on.

Figure 4 shows the resulting LF (lower panel). Following the analysis performed in this Section, FR I galaxies have been furtherly divided into lined (E+AGN) and early-type galaxies in order to show any systematic difference in the LF trend. The result for early-type galaxies is represented by the filled circles in the upper panel of Figure 4 while, due to the paucity of sources, we do not show the LF behaviour in the case of lined FR I.

The dashed lines indicate the predictions of one of the models of Dunlop & Peacock (1990; hereafter DP90), which provides an alternative way of parameterizing pure luminosity evolution and assumes positive luminosity evolution for all steep-spectrum sources, regardless of their power. The particular model among those proposed by DP90 (but also see Rowan-Robinson et al. 1993) considers a luminosity function of the form

$$\Phi(P, z) = \Phi_{\text{SP}}(P) + \Phi_{\text{ELL}}(P, z), \quad (2)$$

where

$$\Phi_{\text{ELL}}(P, z) = 10^{-6.91} / \left\{ [P_{1.4}/P_c(z)]^{0.69} + [P_{1.4}/P_c(z)]^{2.17} \right\} \quad (3)$$

taken at  $z = 0$  gives the local LF for steep spectrum

FR I+FR II sources, and  $\log P_c(z) = 26.22 + 1.26z - 0.26z^2$  (given in  $\text{W}^{-1} \text{Hz}^{-1}$ ) is the evolving “break” luminosity.  $\Phi_{\text{SP}}(P)$  is the non-evolving LF for the spiral/irregular galaxy population. Since all the sources in the FR I sample appear to have spectra with a continuum typical of early-type galaxies, we neglect this last term in equation (2) and only consider the predictions for the population of ellipticals (i.e.  $\Phi(P, z) \equiv \Phi_{\text{ELL}}(P, z)$ ).

As Figure 4 (filled circles) shows, the agreement between data and model is good both in the case of the whole sample and for early-type galaxies only (where we have multiplied the measured LF by the factor  $1/0.78$  to account for the percentage of early-type sources amongst FR I galaxies).

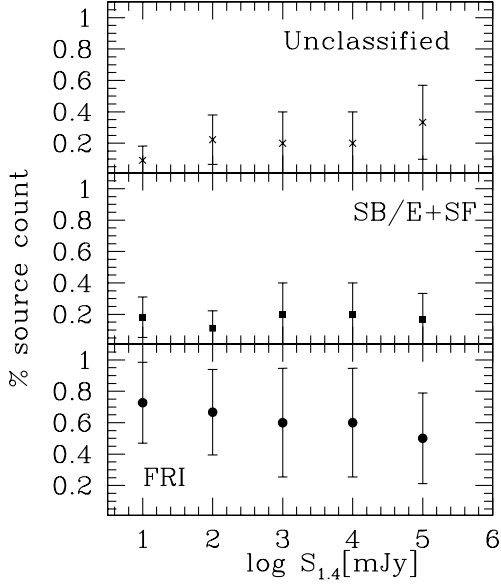
In order to test the effects of luminosity evolution on the calculations of the local LF, the upper panel of Figure 4 also presents (in open circles) the results obtained for the sample of early-type FR I galaxies under the assumption of negligible evolution of the population. In this case the data points shift to the right-hand side of the plot, resulting in an overprediction of the number of low-power radio sources found locally (e.g. Toffolatti et al., 1987) and illustrated by the dashed line in Figure 4.

We also note that integration of the DP90 LF in the interval  $10^{23} \leq P \leq 10^{25}$  predicts  $4 \pm 2$  objects to be found in the observed area and for that luminosity range up to  $z = 0.3$ , consistent with our findings for very few detections of higher-power (FR II) sources at low-redshifts.

## 4 NUMBER COUNTS

As a final step we analyze the relative contribution of different populations to the number counts. Figure 5 shows the percentage of source counts for the different classes of objects included in our spectroscopic sample up to  $S_{1.4\text{GHz}} = 6$  mJy (note that here we have not included any redshift cut), where the sample loses statistical meaning due to the paucity of sources. It is interesting to note that, for *any* value of the flux, the sum of FR I galaxies and unclassified objects accounts for  $\gtrsim 90$  per cent of the radio sources with an optical identification, while starburst galaxies only constitute a small portion of the sample ( $\lesssim 10$  per cent for  $S \lesssim 3$  mJy and  $z \lesssim 0.05$ , none beyond these values). Note that – as the procedure for spectra acquisition of the radio sources of this sample was performed without prior photometric identification – in principle MA2000 could have obtained spectroscopic information for sources with strong emission lines (unless heavily obscured) regardless their optical brightness. This implies that the sample is more likely to be biased against FR I galaxies (in general ellipticals with no or weak emission lines) than starbursts, which makes our conclusion on the relative absence of starburst galaxies in the sample even stronger. Similar results on the small contribution of starburst galaxies to the radio population at mJy level were obtained by Gruppioni et al. (1998) and Georgakakis et al. (1999).

At this point it is also compelling to examine the constraints on the evolutionary degree of the FR I population from the source number counts. Under the assumption of a luminosity evolution of the form  $\exp^{t(z)/\tau}$  (see Section 3), integration of the local LF – expressed in eq.(3) with  $P_c(z) \equiv P_c(0)$  – over the luminosities  $10^{21} \leq P \leq 10^{24}$  [W



**Figure 5.** Percentage of source counts as a function of flux at 1.4 GHz for the different classes of objects discussed in the paper. In the middle panel, starburst galaxies only appear for  $S \lesssim 3$  mJy.

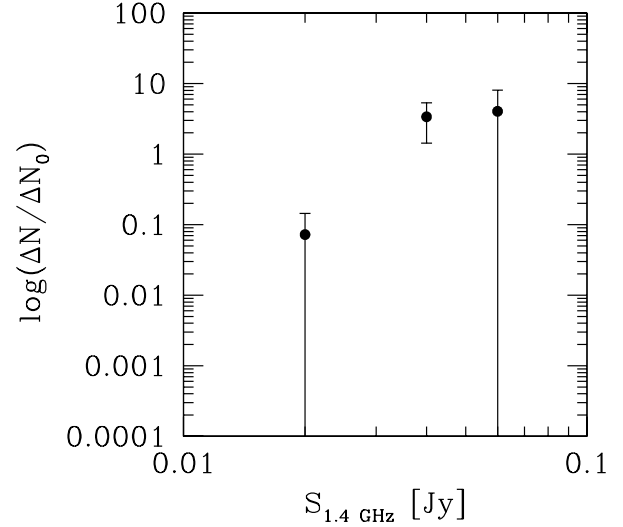
$\text{Hz}^{-1}\text{sr}^{-1}$ ] typical of the FR I population, leads to a total number of sources between  $0 \leq z \leq 3$ , on an area of  $8 \times \pi\theta^2$  (with  $\theta = 1^\circ$  - see MA2000), respectively of 62, 488 and 7205 for  $\tau = 10$  (i.e. no evolution), 0.17 and 0.06. These predictions have to be compared with the value of 656 which is the actual number of objects from the FIRST survey (corrected for the 80 per cent level of completeness of the radio sample at 1 mJy) that have been found in the considered area. Both the values of  $\tau$  describing no- and strong-evolution seem to be ruled out as they respectively grossly underpredict and overpredict the observed integrated number counts, while a better agreement with the data is obtained for  $\tau = 0.17$ . Note that the two values which have been ruled out by these observational constraints on the integral number counts were those respectively obtained by analyzing the evolutionary properties of the sub-class of early-type galaxies ( $\tau = 0.06$ ) and of the “enlarged” population of FR I ( $\tau = 10$ ) - where in this case sources were considered to belong to the latter class merely on the basis of their radio power and morphology (see Section 3).

On the other hand,  $\tau = 0.17$  well describes the shape of the counts distribution at 1.4 GHz below  $\sim 1$  Jy (Silva et al., 2001) and - together with a LF of the form described by eq.(3) - can reproduce the number of FR I sources (with  $P \geq 10^{21} [\text{W Hz}^{-1}\text{sr}^{-1}]$  and  $z \leq 0.3$ ) per redshift interval ( $\Delta z = 0.1$ , see Table 2), found for the sample described in this Paper. We therefore conclude that the same degree of luminosity evolution derived from a  $\langle V/V_{\text{max}} \rangle$  analysis of the FR I population is also needed to provide both the correct total number of sources and the shape of the counts for  $S_{1.4\text{GHz}} \geq 1$  mJy.

Finally, let us consider the above results in the light of the findings for beamed objects, according to radio-loud unification models, as the present sample extends the source counts to significantly lower fluxes with respect to the  $\sim$  Jy samples used for these analysis so far. In Figure 6 we report

**Table 2.** Number of FR I sources (with  $P \geq 10^{21} [\text{W Hz}^{-1}\text{sr}^{-1}]$ ) per redshift interval predicted by a LF of the form expressed by equation (3) for an evolution parameter  $\tau = 0.17$  as compared with the observational findings from the spectroscopic sample.

Redshift Interval	Predicted	Observed
$0 < z \leq 0.1$	1.26	1
$0.1 < z \leq 0.2$	6.3	7
$0.2 < z \leq 0.3$	13.2	10



**Figure 6.** The differential number counts for type I RL, normalized according to Padovani & Urry (1992) ( $\Delta N_0 = 17(S/\text{Jy})^{-2.5} \text{Jy}^{-1} \text{sr}^{-1}$ ).

the differential number counts for type I RL sources. Our findings are in marginal agreement ( $\sim 2.5 \sigma$ ) with the extrapolation to lower fluxes of beaming models (e.g. Padovani & Urry 1992). Furthermore a cut-off in the counts is observed at flux levels  $< 40$  mJy consistently with the above model predictions.

## 5 CONCLUSIONS

In this paper we used the set of data described in MA2000 to derive the radio-properties of different classes of radio objects at mJy level. Our main conclusions are as follows:

- 1) The majority of the sample (between  $\sim 70$  and  $\sim 90$  per cent, where the lower limit is obtained under the assumption of all the unclassified objects to belong to the population of low-power BL Lacs, while the upper limit corresponds to the case for all the unclassified objects to be low signal-to-noise-spectra early-type galaxies), independent of the flux level up to  $S_{1.4\text{GHz}} \simeq 10$  mJy, is made of FR I galaxies. This class includes sources with optical spectra typical of early-type galaxies, both with and without emission lines arising from AGN activity.
- 2) Within the completeness limit of the sample, the population of FR I as a whole shows some degree of luminosity

evolution (at  $1\sigma$  confidence level). This is also found if one lowers the redshift limit for completeness and ensures the stability of the result. The degree of evolution is described by an evolution parameter  $\tau \sim 0.17$  and can correctly reproduce both the integral and differential source counts for fluxes  $S \geq 1$  mJy.

3) Within the population of FR I, it is found that the sub-class of FR I sources with optical spectra typical of early-type galaxies is positively evolving at the  $2\sigma$  confidence level, with  $\langle V/V_{\max} \rangle \simeq 0.60$ . An opposite behaviour is instead seen for lined (E+AGN) FR I galaxies, for which  $\langle V/V_{\max} \rangle \simeq 0.35$ .

4) Models for the local LF can account for the data both in the case of the whole sample of FR I and for early-type galaxies down to powers  $P_{1.4\text{GHz}} \sim 10^{21}$  [W Hz $^{-1}$ sr $^{-1}$ ].

5) Results on type I RL appear to be marginally consistent with both the number counts and the low flux cutoff predicted by the extrapolation of Jy level results by beaming models.

6) The contribution of starburst galaxies at such flux limits is still negligible, of the order of less than  $\sim 10$  per cent for  $S \lesssim 3$  mJy and  $z \lesssim 0.05$ , decreasing to zero beyond these values. This is to be expected if one considers the distribution of radio-to-optical ratios for the different mJy to sub-mJy surveys available in literature. A comparative analysis performed by Prandoni et al. (2001), in fact shows the population of star-burst galaxies to dramatically increase for decreasing  $S \leq 1$  mJy radio fluxes and very bright optical magnitudes ( $I \leq 17.5$ ).

Within this scenario, the population of lined galaxies plays a very important role. A sharp distinction between galaxies with spectra dominated by signatures of AGN activity and those showing features due to star formation has been proved not to be an easy task (see e.g. Rola, Terlevich & Terlevich, 1997). This is mainly caused by the existence of numerous “composite” galaxies containing both an event of intense star-formation and an AGN (Hill et al., 2001). In the sample presented in this work, there seems to be a smooth transition (in terms of radio power, radio-to-optical ratio and even redshift) between lined galaxies of AGN and star-forming origin, so that this class of objects as a whole could be seen as a bridge between AGN-dominated sources and pure starbursts.

One might then envisage a connection with the apparent cosmological trend amongst galaxies. In particular the low activity galactic nuclei, possibly associated with lower efficiency, might be associated with the presence of ongoing star formation giving rise to late-type host galaxies at lower redshifts. On the contrary, higher nuclear powers would plausibly quench the processing of gas into stars at earlier epochs.

Note that different evolutionary properties seem to characterize BL Lacs selected in different bands: X-ray selected lower power objects (whose synchrotron emission peaks at higher frequencies; Giommi & Padovani 1994; Fossati et al. 1998) which are negatively evolving, and more powerful radio selected BL Lac (peaking at lower frequencies) consistent with no or marginally positive evolution (e.g. Urry & Padovani 1995).

The above conclusions (especially those in 2 and 3) obviously strongly rely on the completeness and/or statistical

significance of the sample under consideration. As already discussed in Section 2, a possible cause of incompleteness might stem from the existence of  $R > 18.6$  and  $z \leq 0.3$  sources – possibly associated with some of the seven unclassified objects in MA2000 – for which no spectroscopic identification was possible.

Due to the procedure for spectra acquisition performed by MA2000, we can reasonably assume these objects to belong to the class of early-type galaxies, as the presence of emission lines of whatever origin would have allowed redshift measurements for objects much fainter than  $R=18.6$ . These early-type galaxies would then most likely exhibit redshifts  $\gtrsim 0.2$ , since they are not expected to differ by more than a factor  $\sim 6\sigma$  from the  $R$ - $z$  relationship found for passive radio galaxies. This implies all these sources to show values  $V/V_{\max} > 0.5$ . It therefore follows that the eventual presence of these objects in our sample would have just strengthened the conclusions for a positive evolution of early-type galaxies, while leaving the findings for a negative evolution of the lined (E+AGN) FRI population unaltered. Furthermore, results obtained for the (mild) evolution of the FR I population are confirmed by a completely independent analysis performed on the effects of evolution on the integral and differential number counts for sources with  $S \geq 1$  mJy. And also, our findings on the radio luminosity function are not only in agreement with model predictions, but also with results from much wider samples (see e.g. Magliocchetti et al., 2001).

While the above discussion assesses the goodness of the sample described in this work, it is nevertheless clear that it only constitutes a small fraction of the observable radio sources. This stresses the need for more and better data – probing intermediate-to-high redshifts – to come from future surveys in order to achieve more precise and quantitative conclusions on extremely important issues for both radio astronomy and cosmology such as the evolution of the FR I population and its connection with different BL Lacs flavour.

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